EUV Source System Development Update: Advancing Along the Path to HVM

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ABSTRACT

The EUV light source has been characterized as the top-priority critical issue facing the viability of EUV lithography. Cymer's extensive EUV source development efforts have focused both on the technical feasibility of various approaches as well as the critical issue of commercial feasibility to reach high volume manufacturing (HVM) requirements. We present a comprehensive summary of performance data from a state-of-the-art operational EUV source that thoroughly characterizes technical issues such as conversion efficiency, source material delivery, collector coatings, protection techniques and the path to higher and higher EUV power. Additionally, we present analysis of this performance data when compared to HVM requirements. Finally, we also briefly investigate the associated implications of the cost of consumables (COC) for a production EUV light source.

Keywords: EUV source, EUV lithography, COC

1. INTRODUCTION

This paper summarizes Cymer's assessment of the technical viability of both discharge produced plasma (DPP) and laser produced plasma (LPP) light source concepts to meet projected HVM requirements. We also describe Cymer's progress in developing an LPP based source in support of the introduction of EUV lithography at the 32nm process node.

It is expected that HVM EUV lithography light sources will generate the required 13.5nm radiation by depositing laser or electrical energy into a source element, such as xenon (Xe), tin (Sn) or lithium (Li); creating a highly ionized plasma with electron temperatures of several 10's of eV. The energetic radiation created by the decay of these ions is emitted into all directions and is collected by a mirror (either at grazing incidence or at normal incidence) and focused to an intermediate point from where it is relayed to the scanner optics and ultimately to the wafer.

Due to its overall electrical efficiency and simplicity, Cymer's EUV development efforts have focused on a dense plasma focus (DPF) type of DPP source using xenon as its source element.[1-3] Due to configuration geometries, DPF source designs must continually balance the desire to increase electrode size to maximize heat extraction with the desire to reduce electrode size to decrease the size of EUV source plasma. These design tradeoffs result in systems that do not allow the use of source spatial combination as a scaling technique to reach higher source powers. Given these challenges, Cymer began researching alternative source elements in order to increase the conversion efficiency of the discharge source [4,5] and also the possibility of LPP source technologies to meet the requirements for HVM systems. Cymer's efforts to improve the thermal extraction at the electrode resulted in the ability to extract over 20 kilowatts (KW) from source electrodes with a reasonably sized source plasma.[4,7] Unfortunately even this extraction level is below that required to reach HVM source powers. These levels are at the extreme limits of what can be reached with presently known material and cooling technologies.

Based upon the results of our investigations into alternative source elements and system architectures, Cymer decided that the best path to an HVM capable EUV source is through the use of a novel LPP concept. This decision was also based upon the expectation that the requirements for the ultimate HVM products will be in excess of those predicted today and far beyond the capability of DPF technology.

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2. SYSTEM CONCEPT

Cymer's system concept is shown schematically in Figure 1. The concept uses Li as the source element material coupled with an excimer-based drive laser.

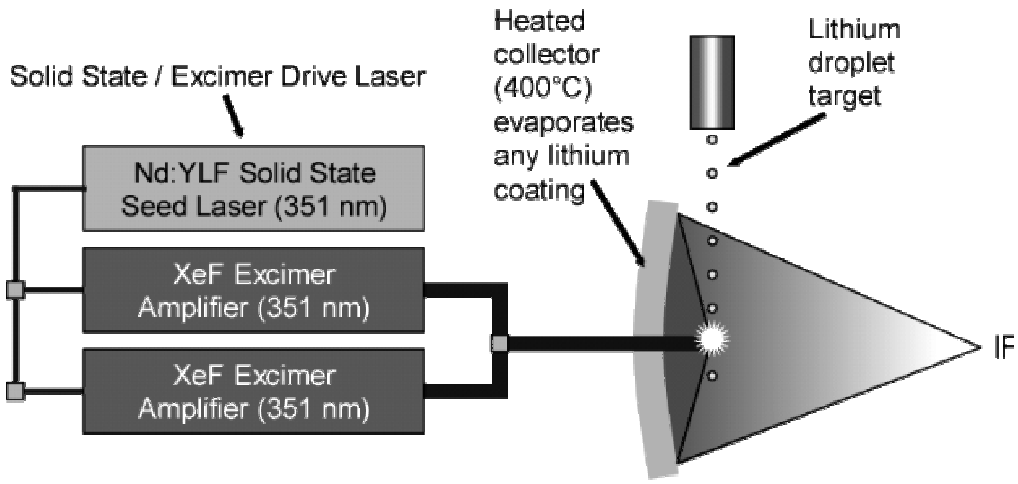


Figure 1. Cymer EUV Source Concept

Lithium is an ideal source element due to its high conversion efficiency (CE) and it's capability to be evaporated from the surface of the collector mirror at relatively low temperatures. The preferred means to introduce the target material is by way of a stream of individual droplets.

The drive laser consists of a frequency tripled Nd:YLF Master Oscillator (MO) coupled to two xenon fluoride (XeF) excimer power amplifiers (PA) firing in a time-interleaved fashion. This configuration combines the solid-state laser benefits of high-frequency operation and excellent beam quality with the lower cost and high reliability of gas discharge excimer power amplifiers.

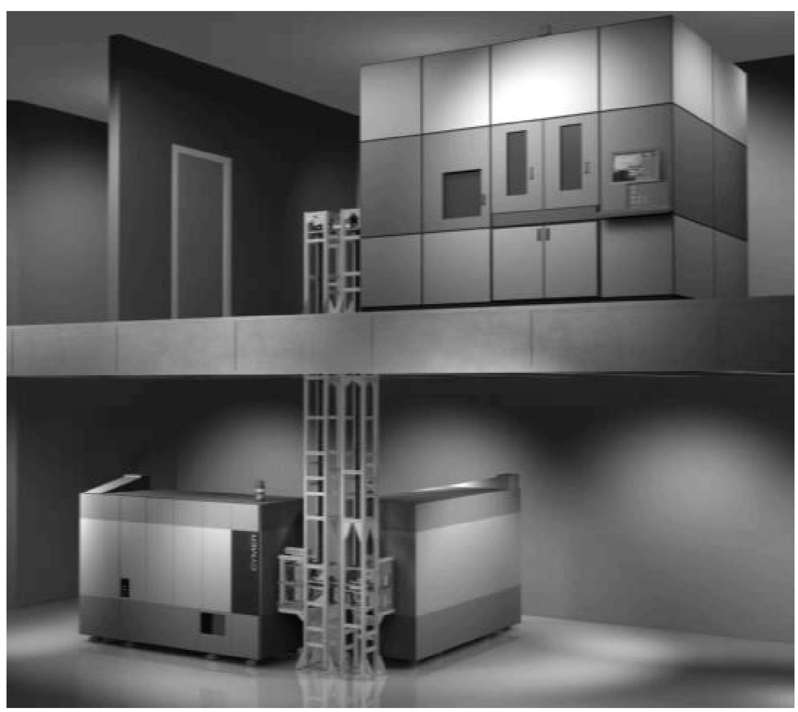


Figure 2. Artist's rendition of the HVM System concept

Figure 2 depicts our concept for a HVM system that incorporates two drive lasers located in a sub-fab configuration. A beam transport system (BTS) combines and delivers the laser beams to the source chamber. It also compensates for slow drifts between each of the drive laser amplifier chains and the target system. Due to the nature of EUV radiation, the source must be integrated within the lithography tool. The source chamber contains a heated, five steradian, normal incidence mirror used to collect the EUV emission and direct it into the lithography tool. It also contains a

lithium target delivery and recovery system, collector mirror protection system, and supporting metrology systems.

3. DESCRIPTION OF KEY SYSTEM ELEMENTS

Lithium as a Target Material

Figure 3 plots laboratory measurements of lithium CE as a function of intensity for a variety of drive laser wavelengths. On the right side of the figure is a comparison of these measurements to modeling results. The general shape shows good agreement between the model and laboratory CE vs. wavelength measurements with the absolute measurements slightly exceeding the model calculations. Even in this non-optimized condition lithium's CE is high, approaching 3% into 2π steradian and a 2% bandwidth and is relatively insensitive to laser wavelengths in the range from 266nm to 1.064μm. This CE value is similar to that reported for Sn and much higher than the CE for Xe.

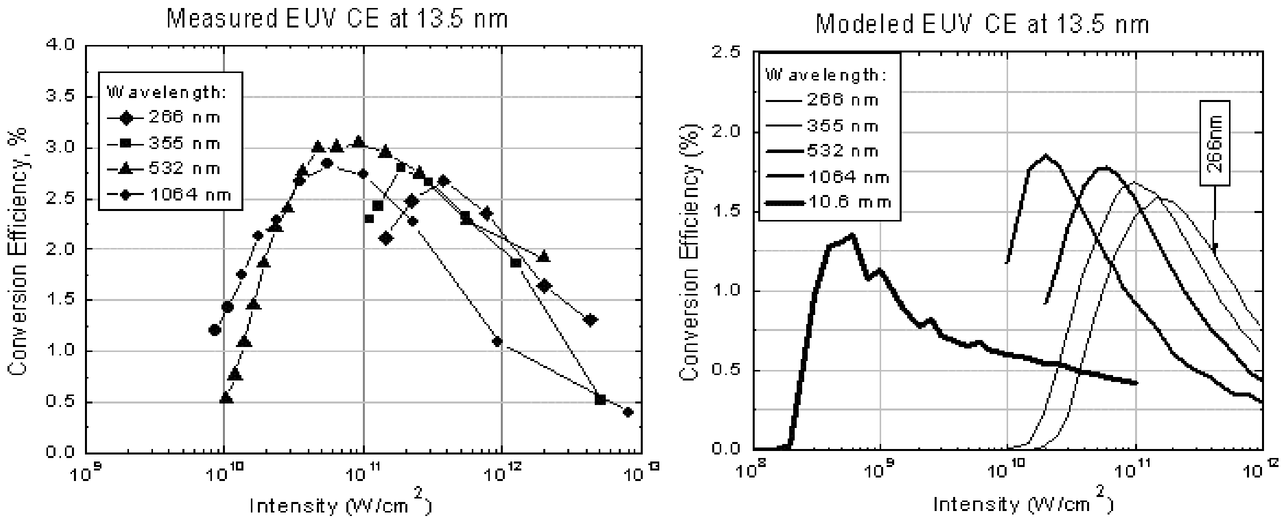


Figure 3 Lithium Conversion Efficiency measurements and model projections vs. wavelength.

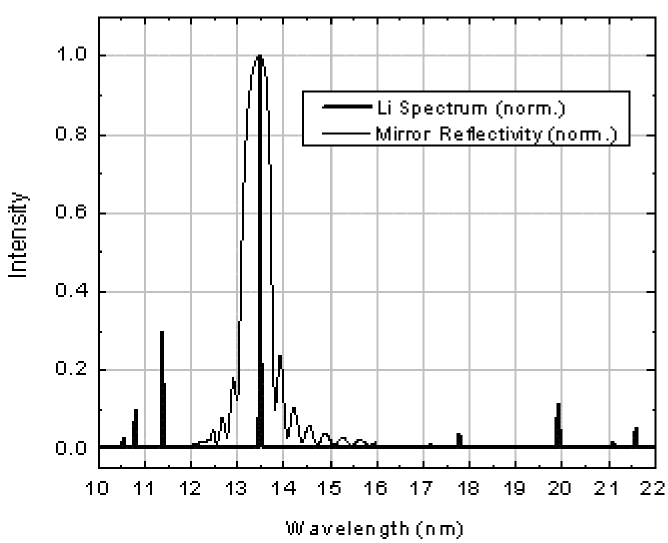


Figure 4 Measured EUV spectrum from a planar Lithium target.

Figure 4 shows the very narrow spectral output of lithium peaked at 13.5nm. This strong emission line is centered in the reflectivity curve for the planned Multilayer Mirrors (MLM). Since the spectrum is significantly narrower than either Xe or Sn it supports more variation in the central wavelength for the numerous mirrors within the scanner's optical system without additional loss of transmitted EUV power to the wafer. Measurements comparing the spectral output from Sn and Li in the EUV range and the ultraviolet-visible band from 200 to 800nm also show that lithium has much lower integrated spectral output in these bands, possibly eliminating the need for spectral purity filters.

Target Delivery

To support initial EUV source experiments, a liquid metal droplet generator has been developed that can operate with a variety of liquid metals.[11] Nearly all materials exposed to the source chamber are stainless steel, making it UHV compatible. Figure 5 shows the generator containing a large upper liquid reservoir and a droplet generator in its lower part. The assembly contains integral heater elements and can be uniformly heated up to 250 °C to accommodate low melting point metals.

Prior to operation the upper reservoir is filled with the desired target material. Operating frequencies from 12 to 48 kilohertz have been demonstrated with a working distance of 50 mm. Both tin and lithium droplets have successfully been produced. The run time is currently limited by the capacity of the liquid reservoir and, as expected, varies greatly with droplet diameter and jet velocity.

Figure 5. Liquid metal droplet generator assembly.

Drive laser

Fortunately, the 351nm wavelength of a XeF excimer laser is within lithium's broad conversion efficiency vs. wavelength curve. Cymer has developed a hybrid laser concept where the beam quality and high repetition rate is provided by a tripled Nd:YLF solid-state master oscillator and the required pulse energy is provided by XeF power amplifiers.[14] Figure 6 below show our ability to shift the output wavelength of the tripled Nd:YLF sufficiently to match the XeF gain spectrum.

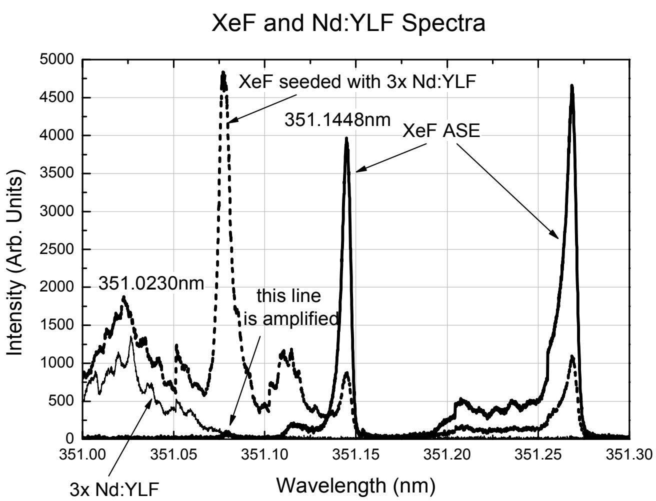


Figure 6. Tripled Nd:YLF output can be shifted sufficiently to match XeF gain.

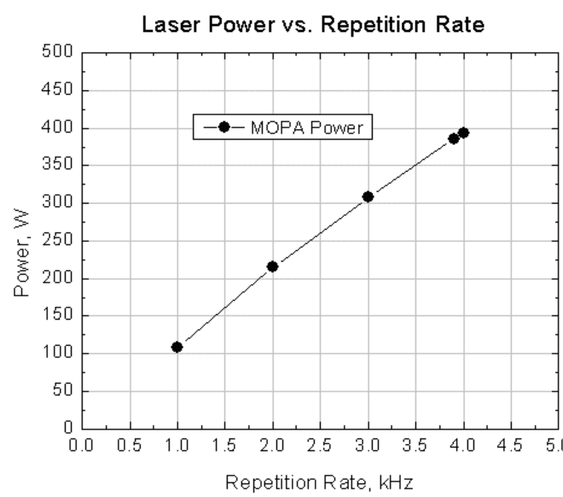


Figure 7. Power output vs. rep-rate for XeF power amplifier shows stable performance at high power

Extensions to Cymer's existing Excimer technology have demonstrated 400W from each power amplifier or 800W total power with the required beam divergence and repetition rates. In addition one development laser, dedicated to the testing of material and laser component life, has been operated for over 9 billion shots with no observed optics degradation. We expect that higher-capacity pulse power and improved discharge chamber technologies will allow the achievement of 2300W at 12kHz by the end of this year, and 3500W per laser at 16kHz in 2007.

Normal Incidence Collector

We are developing both 1.6 steradian sub-aperture collectors and five-steradian full aperture collectors for internal experiments and initial product shipments. The left photograph in Figure 8 shows our initial 320mm diameter, 1.6-steradian subaperture collector undergoing optical test. The right photograph in Figure 9 shows the polished collector mounted and being prepared for thermal validation testing.

The polished collector substrate has been measured to have a high-spatial-frequency roughness of less than 0.3nm. This collector is scheduled to be coated this spring with its MLM coating and will be integrated into our LPP prototype system for testing this summer.

Figure 8. 320mm diameter polished 1.6 steradian collector.

Normal Incidence Collector Coating

In order to heat the collector to 400°C, a MLM coating must be developed that remains stable for 1000's of hours at these elevated temperatures. Several coatings have been developed over the past year, with normal-incidence reflectivities of almost 60% that remain stable at 500°C.[9] Figure 9 shows the reflectivity of one developed coating after being subjected to 400°C for 100 hours.

Normal Incidence Collector Protection

As the ability to generate high EUV powers has increased, the EUV community has focused more of its research effort on developing protection schemes to reach the necessary collector mirror lifetimes. The collector mirror is one of the most costly single elements in the EUV source and its performance is easily degraded by several mechanisms: deposition of the source element and debris; the diffusion of these materials into the MLM structure; and the sputtering of the MLM coating by fast ions and neutrals.

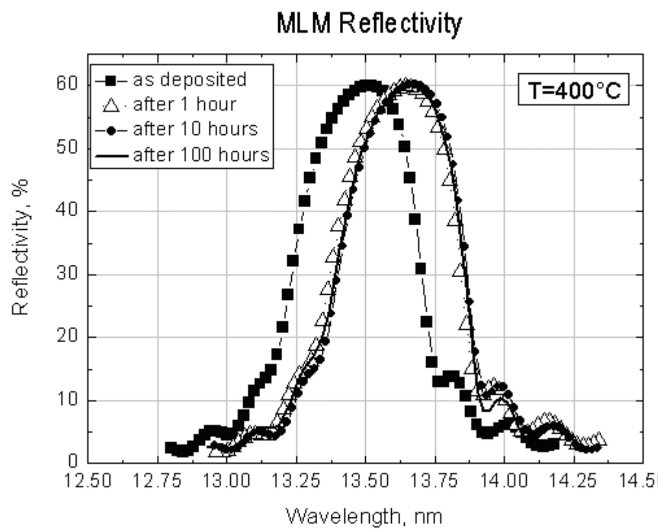


Figure 9 MLM Reflectivity at 13.5 nm after annealing at 400°C.

One of the key advantages of Li as a source material is that it is possible to minimize the amount of Li deposited on the collector surface. This is possible by maintaining the collector surface at a temperature such that the evaporation rate of Li from the collector surface is significantly higher than the influx rate of Li from the vaporized Li droplets. Given our planned droplet sizes and geometries, we calculate that the evaporation rate and influx rate are equal at slightly more than 350°C while a temperature of 400°C would cause the evaporation rate to be an order of magnitude greater than the influx rate.

An investigation of high-temperature materials as diffusion barriers to incorporate into the MLM coating structure has identified several promising candidates. Figure 10 shows a plot of secondary ion mass spectroscopy (SIMS) data from

one of these barrier materials after exposure to Li at 400°C for 10 hours. The data indicate that Li does not significantly diffuse into the MLM and that the periodic MLM structure remains stable.

Another problem that affects the lifetime of the primary collector mirror is sputtering of the MLM coating by high-energy ions generated in the plasma. The physical removal of coating material degrades mirror reflectivity, reducing potential throughput of the lithography tool. In addition, any non-uniform removal of the coating leads to non-uniformities in the angular distribution of the EUV radiation, reducing the uniformity of mask illumination and the potential yield of integrated circuits. In experiments, energies of ions produced in laser plasma reach several kilo-electron-volts (keV). Without collector protection, the mirror lifetime would be limited to several million pulses. At expected repetition rates of 10kHz or more this would correspond to just minutes of production time. Collector mirror lifetimes of >100 billion pulses are believed to be required for commercial viability. Several fast ion energy mitigation techniques are under development at Cymer, including the use of buffer gasses, foil traps as well as electric and magnetic fields.

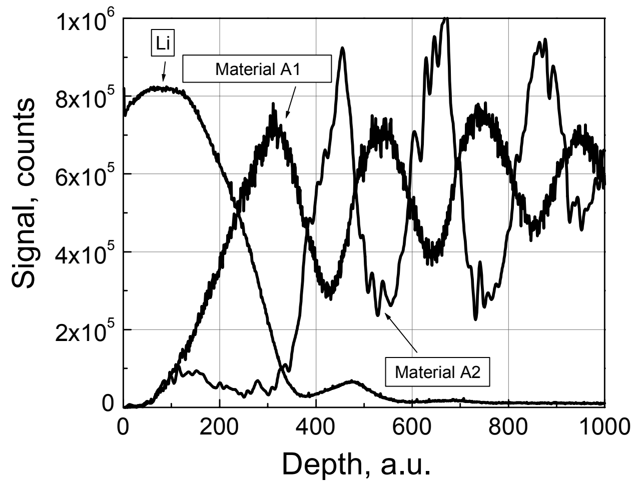


Figure 10. SIMS analysis of EUV MLM made after exposure to Li.

Figure 11 shows experimental results of Sn ion energies produced in an LPP source when measured with a Faraday cup detector after passing through three different collector protection techniques. Two curves on each graph represent the Faraday cup signal with and without debris protection. The signal vs. time represents the intensity of ion flux vs. ion energy. The fastest ions in these experiments have energies of 5 keV and the integral under the curve represents the total ion flux for one laser pulse in each case. The results indicate a reduction in both peak ion energy and total ion flux.

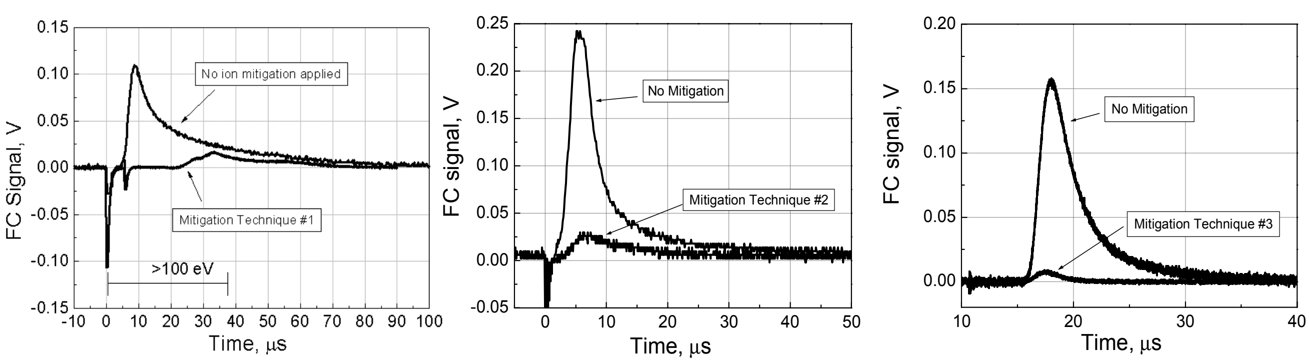


Figure 11. Faraday cup signals recording LPP generated ions through three different ion mitigation techniques.

Lifetime modeling based upon ETS collector erosion measurements [8], predicts that sputtering of the MLM coating will be reduced by more than a factor of 17 for mitigation technique 1, a factor of 12 for mitigation technique 2 and a factor of 19 for mitigation technique 3. Another significant advantage of Li is that at optimum CE laser intensities the ion energies are a factor of 5 lower than for Xe or Sn, and when combined with the sputter yield for lithium, result in a factor of 10 reduction of the sputtering of MLM coatings. Another factor of 10 can be achieved by using several sacrificial coating layers on the MLM. We expect that a combination of these improvements will enable collector mirror lifetimes of 10's of billion pulses, which is acceptable for the first HVM tools.

4. INTEGRATED SYSTEM PERFORMANCE

In addition to developing the necessary subsystems required for a lithium based HVM EUV source, we are also integrating fully functional EUV source systems. These systems are focused on early learning regarding issues such as targeting control and automation so they are based upon simplified subsystems. For example, Tin-droplets are used instead of lithium and the drive laser is a modified version of our standard ArF DUV production lasers. Nonetheless, these are fully functional sources with 4 kHz, 800W drive lasers, automated beam transport systems (BTS) with focusing control, droplet generator, control modules, power modules and a large set of metrology. In Figure 12 below are photographs of the drive laser and source chamber, respectively. The drive laser on the left is a modified version of our standard ArF DUV production lasers. The source chamber on the right includes the target delivery and targeting systems along with a variety of EUV metrology.

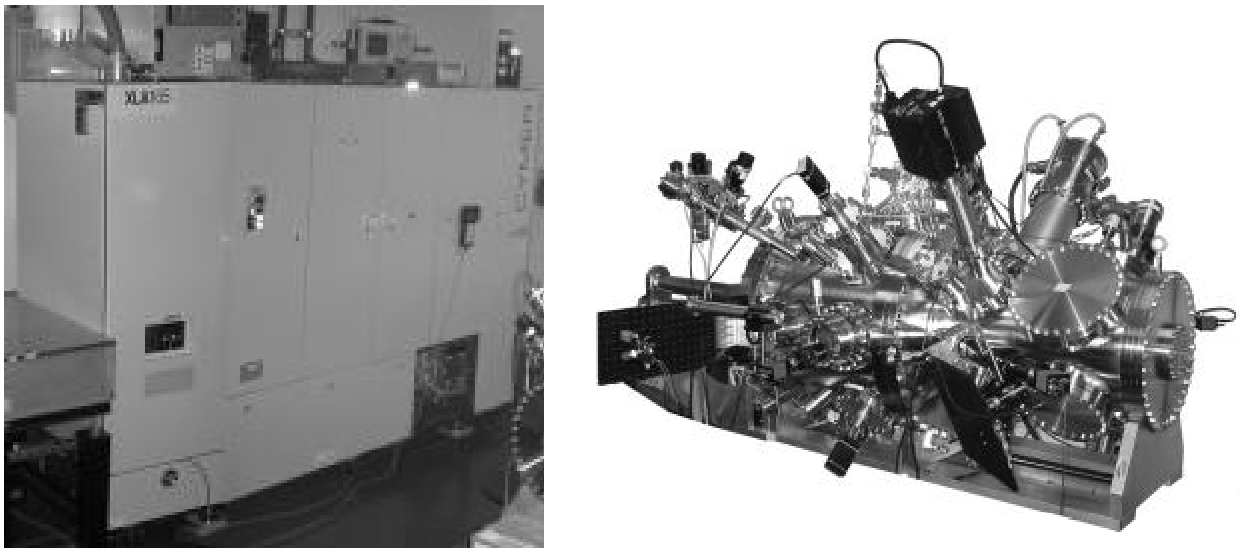
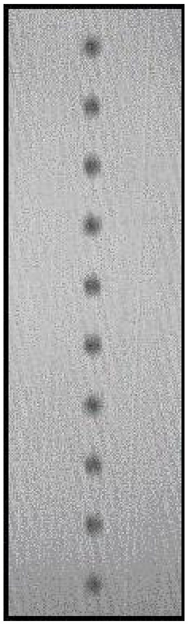


Figure 12. Photographs of the XeF drive laser and source chamber for our prototype LPP system.

An excellent example of work already performed in these source systems, is the introduction of automatic targeting control. The droplet generator produces droplets that are very stable in launch angle, well within the performance requirements but have slightly variable velocities. An example of the droplet stability achieved with our liquid metal droplet generator is shown in Figure 14. As can be seen, the vertical stability is about 200 µm peak to peak. Given the typical droplet diameter of 100 µm and a similar focus size it is obvious that this instability would result in intermittent EUV emission. We have therefore developed a simple automatic droplet targeting system that allows the laser focus to track the motion of the droplets.



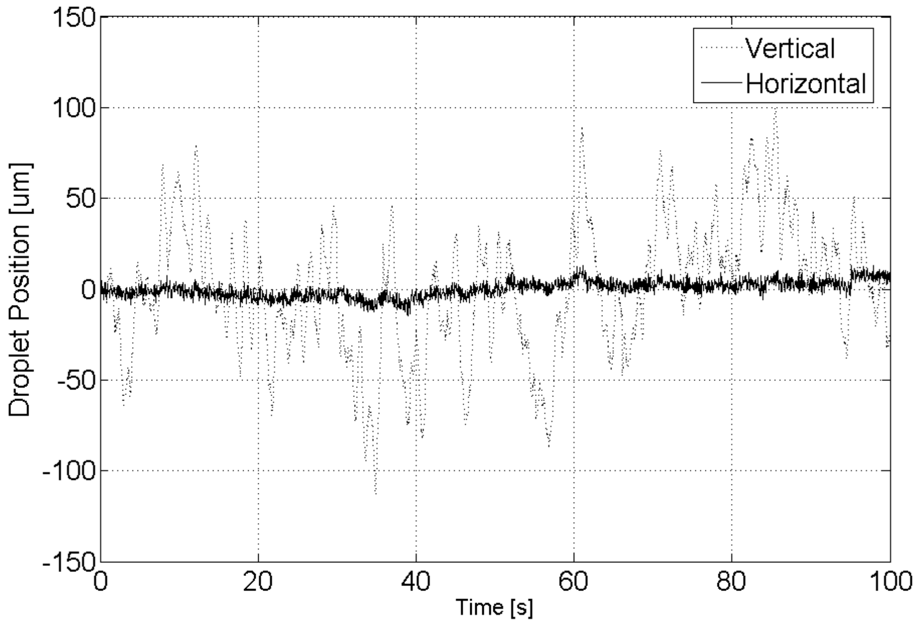


Figure 13. Target droplet position vs. time calculated from single-shot video images taken at 20 Hz 50 mm downstream of the generator with liquid tin and a 50 mm orifice stimulated at 36 kHz. The photo on left shows a typical image of back-illuminated droplet image.

Figure 14 shows typical performance results for EUV energy stability at 1KHz. The dotted line represents open energy-loop performance for a 50 pulses running average, which yields a standard deviation of ±28% (3σ). The solid line is the same data modeled with an energy-feedback algorithm similar to that used by our existing lasers. Such closed loop performance improves the stability to ±0.75% (3σ), which is only a factor 2.5 times the specification for an HVM source. Actual closed-energy-loop capability will be introduced later in the year.

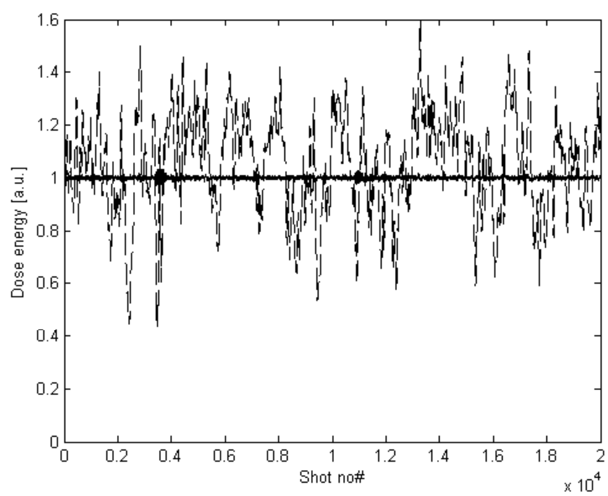


Figure 14. The dashed line illustrates the open loop energy performance of the source at 1kHz operation. The solid line is the simulated closed loop energy performance for the same data.

Since operating a tin plasma at high rep-rates generates considerable debris we have developed protection schemes for the vacuum window through which the laser is focused. Without such protection, the window is fully coated within minutes of operation. This is a problem that must be addressed for Li based sources as well, so we have developed a protection scheme that is compatible with both Sn and Li. Figure 15 shows the effectiveness of this window protection concept in reducing the deposition of source material on the laser delivery window. The window shown on the left was subjected to Sn debris for 2 million pulses without debris protection. The one on the right was subjected to 3 million pulses with debris protection and exhibits no measurable debris.

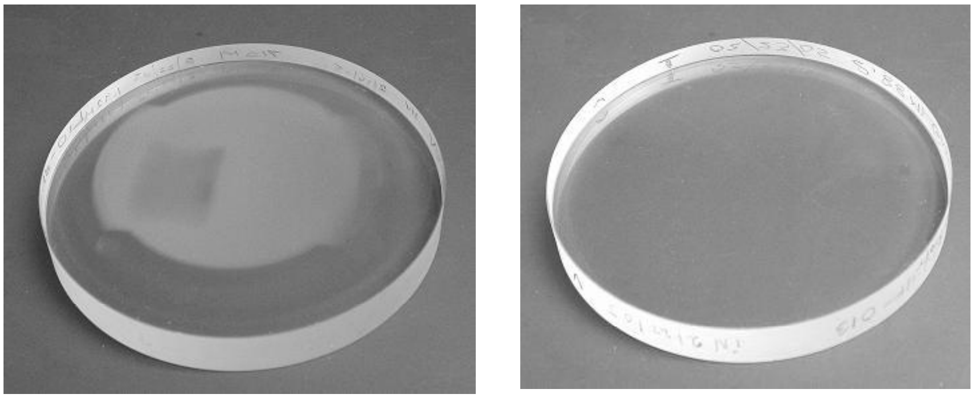


Figure 15. Laser windows with and without window protection.

We have measured the stability of the EUV emission from a series of droplets using our pinhole camera.[10] The camera image in Figure 16 shows 6 sequential in-band EUV images. The EUV emission region is very small, ~90µm FWHM, and the position stability is <10µm.

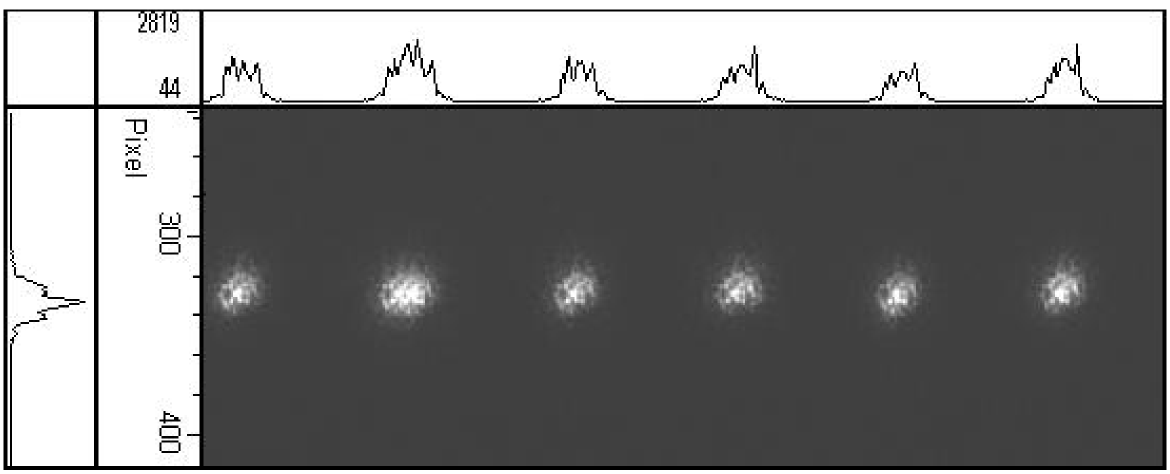


Figure 16. In-band EUV pinhole images of consecutive micro-plasmas from tin droplets generated with 351nm laser light.

5. INDUSTRY REQUIREMENTS

The current joint requirements for a high-volume manufacturing tool [6] are shown in Table 1. It is important to note that the 115W power requirement has two critical assumptions that must be satisfied to be realistic. First, a spectral purity filter, that would remove significant power, is not required by the scanner for distortion-free imaging. Second, and most at risk based on work to date, a 5mJ/cm^2 EUV photo-resist can be developed that provides the necessary resolution with acceptable line-edge-roughness (LER).

Source Characteristic	Requirement
Central wavelength	13.5 nm
EUV Power (2% bandwidth)	115 W
Repetition frequency	≥7 - 10 kHz
Integrated energy stability (3σ, 50 pulses)	+/- 0.3%
Etendue of source output (maximum) *	3.3 mm^{2}str
Max. solid angle input to illuminator*	0.03-0.2 str
Source cleanliness after IF	≥ 30,000 hours
Spectral purity* DUV/UV, 130-400nm IR-Vis, ≥ 400nm	≤ 3 - 7% TBD

Table 1 HVM Joint Source Requirements

A significant challenge for any proposed EUV source to be commercially viable is the system's affordability. Key design requirements include;

1. The selected source material must have a high CE (≥4%).
2. The collector must be large enough to gather the maximum possible EUV radiation from the plasma.
3. The collector must have a high average reflectivity, including the losses at the larger incidence angles, and must exhibit a long life. Furthermore, it should be easily exchanged at a reasonable cost.
4. The drive laser must provide multi-kilowatts of power with reasonable system cost and have sufficient consumable lifetimes to meet cost-of-operation expectations.
5. The laser power must be transmitted with minimal losses from remotely located lasers to the source chamber.
6. The system reliability and maintainability must be in line with semiconductor standards to allow high utilization in volume production

Substantial progress has been made in increasing the output power of both LPP and DPP technologies. But what if the source power requirements increase beyond those projected today to support photo-resists that require 10 or 20 mJ/cm^2 or to provide increased process latitude or to meet the requirements of more advanced future scanners?

Deep ultraviolet (DUV) photolithography history shows that the power required from the laser source did not decrease over time. On the contrary, from the time DUV Excimer lasers were first used in a production environment, the power requirements actually increased six times, as shown in Figure 17.

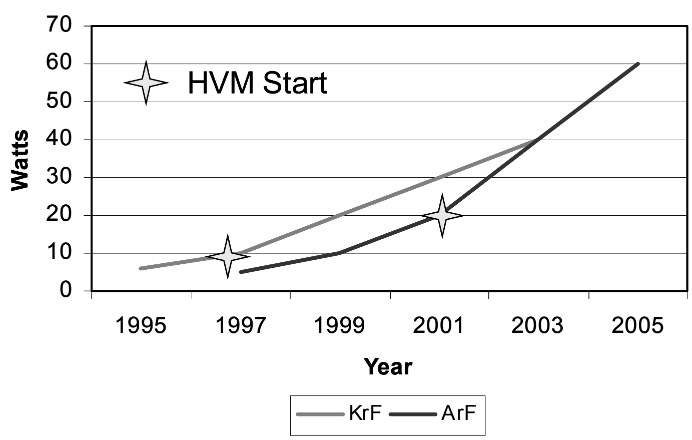


Figure 17. DUV Power Requirements have increased significantly since their introduction into a fab environment.

We believe that a viable EUV source technology must take into account that the power requirements for the ultimate EUV sources will likely be well in excess of the 115W currently projected for high-volume manufacturing. Given these unknowns, a viable concept must offer the required scalability to support the industry.

6. DEVELOPMENT ROADMAP

Our development roadmap is shown in Table 2. By the end of 2005, Cymer plans to have an LPP EUV source with the capability of producing 15W of power at the IF using a single 2300W drive laser. Over the following several years, improvements in laser performance both in the area of energy-per-pulse and repetition rate will ultimately result in a single laser that can produce 3500W. The combination of two such lasers in a system will produce the necessary 7000W of laser power needed to produce the >100W of EUV power at IF required of an HVM source. As the technology matures and device geometries shrink with ever-tighter performance and cost requirements, our roadmap provides the power necessary for the scanners of the future to deliver the required on wafer performance to justify the economics of EUV lithography technology.

Performance Roadmap					
	Beta -	**Beta**	**HVM**	**HVM+**	**HVM++**
Number of laser frames	1	2	2	3	4
Power amplifiers per frame	2	2	2	2	2
Rep rate per amplifier (kHz)	6	6	8	8	8
Drive laser rep rate (kHz)	12	12	16	16	16
Total rep rate (kHz)	12	24	32	48	64
Pulse energy (mJ)	190	210	220	220	220
Drive laser power (W)	**2280**	**5040**	**7040**	**10560**	**14080**
Transmission BTS	96%	96%	96%	96%	96%
In-band CE	2.0%	3.2%	4.0%	4.0%	4.0%
Geometric collection effy (sr)	5	5	5.5	5.5	5.5
Collector obscurations	6%	4%	4%	4%	4%
Collector average reflectivity	50%	50%	50%	50%	50%
Collector Lifetime (k hrs)	1	5	10	10	10
Buffer gas transmission	90%	90%	90%	90%	90%
Total power at IF (W)	**15**	**53**	**102**	**153**	**204**

Table 2. Source Development Roadmap

7. SUMMARY

Li droplets combined with an Excimer laser provide an optimal path to a EUV HVM source. An LPP-based system can meet the anticipated HVM requirements with available scalability for future requirements. The use of lithium as the source material maximizes in-band conversion efficiency and allows for manageable debris mitigation through evaporation and lower source ion energies. Excimer lasers are today's best drive laser solution, with the proven reliability required to meet semiconductor production expectations, an existing global service infrastructure, and a track record of affordable cost of operation. The primary development challenge for a viable source technology continues to be the development of debris mitigation techniques and MLM coatings to provide the necessary collector lifetime and cost to meet lithography production requirements.

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